XVIII. *On Seismic Experiments.*

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[Plate 52.]

The following paper is an account of a series of experiments made at the Akabane Engineering Works, Tokio, for the purpose of investigating a number of phenomena connected with earthquake motion.

In 1851 Mr. Robert Mallet, by means of a number of carefully-performed experiments, determined the velocity with which vibrations were transmitted through various media. These vibrations were produced by exploding charges of gunpowder. (See Report of British Association, 1857, also Philosophical Transactions, 1861, 1862, Appendix). As maximum and minimum velocities obtained in feet per second, Mr. Mallet found

	Feet per second.
In sand	824·915
In solid granite	1664·576

In 1876, at the time of the Hellgate explosions at the entrance to the New York Harbour, experiments were arranged by General Abbott for like determinations. These experiments gave velocities varying between 3,000 and 8,300 feet per second.

By a different series of experiments on the "compressibility of solid cubes" of rock, Mr. Mallet determined "the mean modulus of elasticity of the material," and inferred the fact that "owing to discontinuity of rocky masses as found in nature, nearly $\frac{7}{8}$ of the full velocity is lost." (See 'The Eruption of Vesuvius in 1872,' by Professor Luigi Palmieri, with notes by Robert Mallet, p. 18.)

These determinations of velocity of wave transit are, so far as we are aware, all that has yet been done in the experimental investigation of phenomena connected with the transmission of vibratory motion through the earth's crust.

In the experiments described in this paper the disturbance was produced by allowing a heavy weight to fall from a height which could be varied from zero up to 35 feet.

The following are the principal points towards which we have directed our attention with regard to the resulting vibrations.

1. The difference in the magnitude and character of the motions produced at stations variously situated with regard to the point at which the blow was struck. These stations were sometimes taken on a level plain at different distances from the origin of the motion. At other times they were taken at various points on the side and summit of a hill. They were also taken so that a deep cutting in the form of a pond intervened between the point where the blow was struck and the observing station.
2. The relation between normal and transverse vibration as simultaneously exhibited at various stations.
3. The velocity of transmission of normal and of transverse vibrations.

The Akabane Engineering Works where these experiments were carried on are situated on the southern side of Tokio, upon a flat alluvial plain bordering a low spur running out from one of the table-land-like elevations which characterise certain portions of the city lying at a short distance from the sea board. The soil, with the exception of that which is immediately upon the surface, may be described as a hardened mud, very similar in character to that which is now being deposited in the delta-like formations at the mouths of the various rivers which enter the bay.

The plan which is attached (Plate 52) shows the general arrangement of the works. The buildings which are shaded are built of brick; the others are light structures built of wood. The ball which gave the shock was always dropped at the point A, it weighed 1,710 lbs., and could be conveniently raised up to a height of 35 feet.

The stations where the effects of the blows were observed are on the lines A B, A C, A D, &c.

The stations on these lines are distinguished from each other by numbers indicating their distance in feet from the point A where the ball fell. The only exception to these are the stations on the line J K, which are marked according to their distances in feet from the corner of the pond J.

The sections on the lines A F and A H will give the contours of the hill. The pond has perpendicular walled sides, and is about 10 feet deep. The lines A B, A C, A D are along ground which is practically level. At the commencement of the experiments the ground was somewhat soft, and the ball at the first few blows sank to a considerable depth.

We may here call attention to the fact that the vibrations which we have investigated, as in the case of vibrations produced in Mr. MALLET's experiments by an explosion of gunpowder, are the result of a disturbance produced on the surface of the ground, whereas in actual earthquake motion it is quite possible that the disturbances we feel may have an origin which is deeply seated beneath the superficial crust. The only advantage which we can claim for our method of producing vibrations, as com-

pared with the production of them by the ignition of some explosive material, is that we are able to make a more definite estimate of the force of the blow.

In giving the following results, which have been classified, so far as it was convenient, according to their object, we call attention to the fact that the fall of the ball was, when we could obtain observers and instruments, used to determine several distinct results.

Thus a blow which was used to *measure* the *velocity* along the line A B was used to determine the relative amount of vibration transmitted along various other lines. This remark explains why the same fall of the ball is referred to in different groups of experiments. These experiments were first projected in November, 1880. During the month of December instruments, &c., were being prepared and the necessary arrangements entered into for the carrying of them out. Of days actually spent in making experiments there were nine. As in some cases, after a set of experiments, new base lines had to be measured, old instruments altered, or new ones designed for the improvements of the work already done, or for the carrying out of new work, and as at the same time much college work, &c., had to be attended to, these nine days were not consecutive.

In consequence of having on each day of experiment to relay our telegraph, reset the various instruments, obtain coolies to work at the windlass in winding up the ball, &c., it was but seldom that more than four or five falls could be obtained in one day. The following table shows the numbers of the falls which took place upon each of the days.

EXPERIMENTS at the Akabane Works, Tokio, January and February, 1881.

	Number of falls.
First day	1, 2.
Second day	3, 4, 5, 6, 7, 8.
Third day	9, 10, 11, 12.
Fourth day	13, 14, 15, 16.
Fifth day	17, 18, 19, 20.
Sixth day	21, 22, 23, 24.
Seventh day	25, 26, 27, 28, 29, 30.
Eighth day	31, 32, 33, 34, 35, 36.
Ninth day	37, 38, 39, 40.

The object in giving the above table is that, having numbered our experiments according to the fall of the ball, it can be seen on which day the experiment took place. This is necessary, because after every fall on any particular day the ground on which the ball fell became harder, and this hardening has apparently had its effect in the nature of the records. Also on different days the ground generally varied slightly in its character, according as it had or had not been subjected to severe frost during the previous night.

First Set of Experiments.

These were preliminary experiments to determine the relative amounts of energy received at stations variously situated with regard to the point at which the ball fell.

The general method which was followed in making these experiments was by means of a winch to wind the ball up to a certain height, pull a catch, and allow it to drop.

To observe the amount of vibration which was produced in consequence of this blow, a number of similar bottles containing similar amounts of mercury were employed. One or two of these were placed at each station with an observer, who noted, by means of the seconds' hand of a watch, the length of time that the oscillation produced by the blow continued. These bottles had wide necks, an internal diameter of about 40 millims., and were filled with mercury to a depth equal to their diameter. In order to see the vibration of the mercury distinctly, in some of the experiments a small float consisting of a thin circular piece of sheet iron about 6 millims. in diameter, from the centre of which there was a thin piece of wire projecting up through the neck of the bottle, was placed upon the surface of the mercury.

In consequence of a slight motion in the mercury producing a considerable motion in the ship-like mast of the float, the length of time that the mercury oscillated could be easily noted. These floats were made as similar as possible. After the bottle had been firmly planted on the ground, and the mast of the float remained steady on a position passing through the centre of the neck of the bottle, the whole was covered with a large beaker to act as a shade.

This method of experiment is evidently at its best only capable of giving a relative estimate of the amount of motion at the different observing stations.

I.—Fall of ball on the line A B.

All the bottles, which were numbered from 1 to 6 consecutively, were placed in a row at the 30 feet station. The ball fell from a height of 30·5 feet. Owing to the ground being very soft it sank into the soil for fully 1 foot. All the pointers oscillated for about 20 seconds with the exception of that in bottle number 4, which oscillated for nearly 30 seconds.

II.—Fall of ball on the line A B. Ball fell 30·5 feet.

Number of bottle.	Station.	Time of motion of the mercury.	Remarks.
	feet.	seconds.	
6	30	14 (?)	These observations were not carefully made.
4, 5	100	About 28	
2, 3	200	About 15	

III., IV., and V.—FALLS of ball on the line A D. Ball fell 31 feet.

Number of bottle.	Observer.	Station.	Number of experiment. III. Time of motion.	IV. Time of motion.	V. Time of motion.
		feet.	seconds.	seconds.	seconds.
6 and 3	MILNE . .	100	20	21	22
4 and 5	KINCH . .	200	20	22	. .
4 and 5	KINCH . .	270	Not observed	Not observed	20

VI.—FALL of ball on the line A B. Ball fell 31 feet.

Number of bottle.	Observer.	Station.	Time of motion.
		feet.	seconds.
6 and 3	MILNE . .	100	30
4 and 5	KINCH . .	400	13 and 15

VII. and VIII.—FALL of ball on the line A B. Ball fell 31 feet.

In these experiments the floats were taken out of the bottles and the movement of the surface of the mercury observed directly.

Number of bottle.	Observer.	Station.	Number of experiments. VII. Time of motion.	VIII. Time of motion.
		feet.	seconds.	seconds.
3	MILNE . .	100	13	16
6	NEMBRINI .	300	11	13
4 and 5	KINCH . .	400	8	11

During these last experiments it may be remarked that the observers at the 400 and the 560 feet stations distinctly heard the sound of the ball striking the ground before seeing any motion in the mercury.

IX., X., XI., and XII.—FALLS of ball on the line A B. Ball fell 35 feet upon a large block of iron which had been placed in the hole made by the ball.

In these experiments a number of similar saucers containing equal quantities of mercury were substituted for the bottles.

Station.	Number of the experiment.							
	IX.		X.		XI.		XII.	
	Time of motion.	Observer.	Time of motion.	Observer.	Time of motion.	Observer.	Time of motion.	Observer.
feet.	seconds.		seconds.		seconds.		seconds.	
100	9	MILNE . .	14	MILNE . .	15	GRAY . .	20	MILNE
300	10	GRAY . .	8 or 9	ANGAS . .	7	ANGAS . .	..	..
450	..	. . . .	5	NEMBRINI .	8	NEMBRINI .	8	NEMBRINI

During the XI. Experiment a saucer of mercury was observed at the 75 feet station on the line J K by BRINDLEY, but no motion was detected.

XIII., XIV., XV., and XVI.—FALLS of ball on the line J K to show the effect of the pond in cutting off the transmission of vibrations. Ball fell 35 feet upon the block of iron, which had been almost driven out of sight.

Station.	Number of the experiment.							
	XIII.		XIV.		XV.		XVI.	
	Time of motion.	Observer.	Time of motion.	Observer.	Time of motion.	Observer.	Time of motion.	Observer.
feet.	seconds.		seconds.		seconds.		seconds.	
0	9	MILNE . .	10	NEMBRINI .	..	. . . .	..	..
30	8	TAMAKI .	10	TAMAKI .	..	. . . .	..	..
60	..	. . . .	5	MILNE . .	9	NEMBRINI .	9	NEMBRINI
90	..	. . . .	..	. . . .	1	TAMAKI .	0	TAMAKI
120	..	. . . .	..	. . . .	0	MILNE . .	0	MILNE

XVII.—FALL of ball on the line A H (see section). Ball fell 35 feet.

Station 140 feet. When the ball fell the observer felt a strong shake and the mercury in the saucer was in consequence put in motion for 12 seconds.

Station 100 feet. Here also a strong shake was felt, but as the ground was in a continuous state of vibration due to the working of a neighbouring engine it was difficult to say how much of the motion produced in the mercury was alone due to the blow.

XVIII. and XIX.—FALL of ball. Ball fell 35 feet.
Line A F and line A E (see sections).

	XVIII.		XIX.		Mean.
	Time of motion.	Observer.	Time of motion.	Observer.	
	seconds.		seconds.		
Line A F, station 180 .	24	NEMBRINI .	10	MILNE . .	17
Line A E, station 130 .	10	MILNE . .	13	NEMBRINI .	11

These experiments apparently show that neither a small hill nor a cutting have the effect of preventing the propagation of vibrations.

This brings us to the end of all the experiments where the movement in a vessel of mercury was used as an indicator of the relative amounts of motion which were transmitted to the various stations. The only value of these observations, which were necessarily somewhat rough, is the indication they give as to where the motion was relatively strong, slight, hardly perceptible, &c., and of points where it had died out or owing to the configuration of the ground had been unable to reach.

SECOND SET OF EXPERIMENTS.

In the following three experiments, in consequence of having employed a seismometer, we obtained a close approximation to the maximum amplitude of the motion of an earth particle. These indications also showed us whether the movements recorded were due to normal or transverse vibrations.

The seismometer may be briefly described as follows :—

A frame having a spherical base supports on a pivot at a point a little above the centre of curvature of this base a heavy lead ring, of such a weight that when placed at the centre of oscillation of the frame it produces approximately neutral equilibrium.

To the edge of this ring, at points distant from each other by one quarter the circumference, two threads were attached. These threads were carried outwards in the direction of the radii through their points of attachment and passed over light pulleys attached to a second frame which was fixed to the earth. When this second frame was moved, in consequence of the motion of the earth, the ring, by its inertia, caused the threads to turn the pulleys; these pulleys were furnished with indices giving a multiplication of 40 for the motion on one side of the normal position of the earth.

Experiment XX.—Ball fell 35 feet.

Line A E. Station 130 feet.

The seismometer was so placed that the thread of one pointer bore about E. and W., or was parallel to the edge of the pond, whilst the thread of the second pointer was at right angles to the first thread.

The second pointer moved about 1 millim. as if by a transverse wave.

This shows a total motion of ·05 millim. in the ground.

Experiment XXI.—Ball fell 35 feet.

Line A E. Station 130 feet.

The seismometer was so placed that one thread pointed directly to the point where the ball fell. At the time of the shock the pointer of this thread did not move, but the pointer at right angles moved about 1 millim., again indicating that the instrument had only been affected by transversal vibrations.

Experiment XXII.—Ball fell 35 feet.

Line A H. 100 feet station.

The seismometer was so placed that the thread of one pointer was in the direction of the weight, the thread of the other pointer being at right angles to this direction.

Each of the pointers moved about 2 millims.

Third Set of Experiments.

In the following experiments a clear graphical distinction between normal and transverse vibrations was obtained at a number of different stations, together with the maximum amplitudes of each of these two distinct movements.

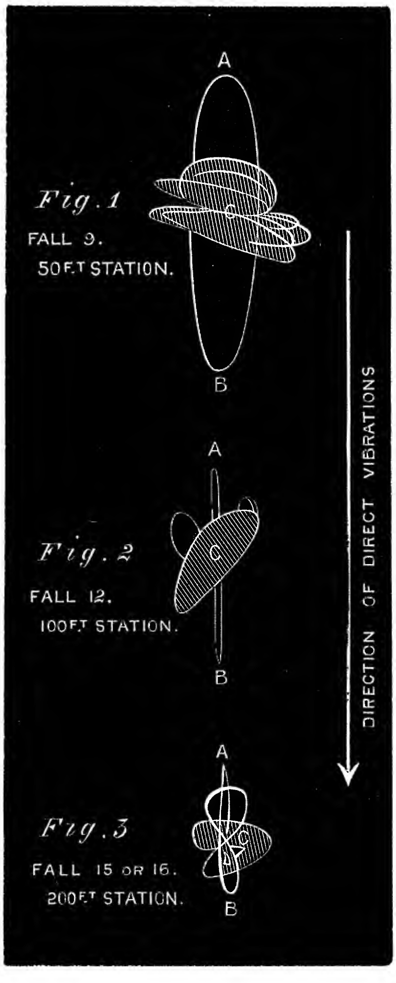
The instrument employed in obtaining these records was a small rolling sphere seismograph, writing its movements directly upon a smoked glass plate by means of a pointer.

The instrument may be described as follows:—At the centre of curvature of a small hemisphere a heavy lead ring rested on a point. To the hemisphere a light pointer was attached, of such a length that its end moved ten times as far as the bottom of the hemisphere. At the end of this pointer a sliding needle was arranged so that its point rested against a smoked glass plate, and when moved by the motion of the earth under the sphere, wrote that motion magnified 10 times on the plate.

When the ball fell, the pointer could be seen to make one or more back and forth quick movements in the direction of the line joining the instrument and the point where the ball fell, and then immediately afterwards to change suddenly into a motion which was inclined to the first movements. The records drawn upon the smoked glass plates corresponded with the observed movements.

The only exceptions, which were two in number, where the above description of the motion does not apply, was when the ball only fell a short distance (8 and 11 feet), and the observing point was at the 50 feet station. In these two instances simply a series of long narrow ellipses were drawn, their longer axes being in the direction of the line joining the position of the falling weight and the instrument.

Of the other figures which were drawn we give three examples, each of which show the motion of the ground magnified 85 times. It will be seen that these figures are so arranged that their greatest lengths are parallel. The direction of greatest motion was that of a line joining the instrument and the point where the ball fell.



At the commencement the needle of the pointer was resting at or very near to the centre of the figure C. In all cases when a clear diagram was obtained it moved to A, then down to B, and back again towards C. At or about this point its motion was suddenly deflected. In many cases this deflection took place nearly at right angles to the first motion, as is shown in fig. 1. Here a great number of flattened ellipse-like figures were drawn one on the top of another so as to render this central portion of the diagram confused.

In fig. 2 these central motions were performed in a direction inclined at about 45° to the first motions.

In fig. 3, about which it may be remarked that other diagrams taken at the same station were very similar, a lemniscate-like motion is exceedingly well pronounced.

The shaded portions of these three figures indicate the parts where the lines were so numerous that they could not be distinctly separated from each other.

The stations at which these figures were drawn and the fall of the ball to which they correspond are indicated beneath each.

In the first column of the following table a number is given showing on which fall of the ball the experiment was made. The second column indicates at which station, or the distance in feet from the point where the ball fell, at which the experiment was made—with the exception of the fall No. 23 all these stations are on the line A D.

The third column shows the maximum amplitude of the normal, and the fourth column that of the transverse motion—excepting the falls 27, 28, and 29 (see Remarks), the weight fell 35 feet.

Number of fall.	Station.	Maximum amplitudes.		Remarks.
		Normal vibrations.	Transverse vibrations.	
	feet.	millims.	millims.	
9	50	7	4·5	The ball fell on a block of iron.
10	50	10	2·5	Transverse motion not very distinct.
11	50	10	2·25	,, ,, ,,
12	100	4·5	2	Transverse motion at an angle of about 45° with the normal vibrations. As the ground hardened under the weight, the transverse vibration apparently became less.
13	100	3·5	2·75	The character of the records drawn for these two experiments are very similar, but slightly different from that obtained from Fall No. 12.
14	100	3·5	3	
15	200	2	1·5	These two records appear to be exactly the same, the transverse motion is now more than at right angles to the normal motion.
16	200	2	1·5	
17	100	4·5	2	
18	100	4·25	2·5	
20	150	5	3·5	
21	250	2	1·5	Not completely written.
22	250	1·75	1·75	Somewhat complicated.
23	130	1	1·25	This record was made at the 130 feet station on A E.
26	50	9 (?)	5	The record is somewhat confused.
27	50	8·5	4·5	Ball only fell 25 feet. The record is not good.
29	50	9	2	Ball only fell 11 feet } Transverse measurements represent the breadth of the normal ellipses.
30	50	8	2·5	,, ,, 8 feet }

Fourth Set of Experiments.

In these experiments a pair of horizontal lever seismographs were used to register the motion of the ground. They indicated their motion on smoked glass plates.

From the following brief description of these instruments it will be seen that if one of them was so placed that its pointer was in the direction of the line joining the centre of disturbance and the observing station, it could only fully register transverse vibrations, whereas normal vibrations would not be recorded.

The instruments were therefore placed with their pointers at right angles to each other, one of them pointing directly towards the weight. In this manner one of them was caused to give a full record of normal vibrations and the other of transverse vibrations.

The seismograph here used was almost identical in form with Ewing's "astatic horizontal lever seismograph."

The principle is that of a mass supported on a horizontal arm which can turn freely round a vertical axis. The mass consisted in this case of an iron ring about 5 kilos. in weight, and was pivoted so that it could turn round a vertical axis through its centre at right angles to the plane of the ring. The distance between the axis of the lever and of the mass was about 2 centims., and the length of the index such as to give a multiplication of 12.

The various columns in the following records of the experiments with these instruments have the same meaning as those in the last set of records.

Number of fall.	Station.	Maximum amplitudes.		Remarks.
		Direct.	Transverse.	
	feet.	millims.	millims.	
19	100	7·5 (?)	1·25	
24	50	9	2·5	
25	30	1	..	On the line J K.

Fifth Set of Experiments.

These experiments, which were made on the line A D, chiefly differ from the third set in the fact that the smoked glass plates, instead of being at rest whilst the pointers of the seismographs were indicating the back and forth motions of the ground, were drawn along horizontally by means of clockwork. These plates were strips of glass about 2 feet in length, and from 3 to 6 inches in breadth, carried on a small three-wheeled carriage. This carriage was attached to a strip of paper which was pulled along by means of a Morse telegraph instrument. An advantage in using this

instrument was, that an observer was enabled to tick off very conveniently intervals of time upon the moving strip of paper. When the signal was given for the catch to be pulled to allow the ball to fall, an observer started the clockwork, so that before the ball reached the ground the carriage was fairly in motion. When the observer saw that the pointers of the seismograph had ceased to write, the clock was stopped, and the whole arrangement allowed to stand still until the ball could be again wound up and a second record obtained. In this way several successive records were obtained without the introduction of possible errors due to the resetting of the instruments.

The seismograph employed was either the small rolling sphere seismograph, or a pair of horizontal lever instruments.

When the horizontal lever seismographs were used—they were so placed that one of them could only fully record normal vibrations and the other transversal vibrations—it could be seen that the writing of the normal vibrations commenced slightly before that of the transversal ones. During these experiments, in order to determine the interval of time it had taken for these two sets of vibrations to travel from the falling weight to the station at which the instrument was placed, a third pointer was allowed to rest upon the smoked glass plate close to the pointers of the horizontal lever seismographs. As the plate travelled along, this third pointer, when not interfered with, described a straight line. By means of the shock communicated by the ball to the ground, a specially contrived instrument, which was placed about 10 feet from the point where the ball struck, closed an electric circuit. This closing of a circuit caused an electromagnet to suddenly deflect the third pointer and produce a sudden break or deviation in the line being drawn by it. The instant when the vibrations reached a point 10 feet away from the place where the ball struck the ground was thus very clearly marked upon the smoked glass plates. The time at which they reached the station where the plate was situated, was indicated by the pointers of the seismograph ceasing to draw a straight line and commencing to write the vibrations affecting the instrument to which they belonged. The velocities deduced in this manner for the transmission of normal and transverse vibrations are discussed under the sixth set of experiments.

RECORDS obtained with horizontal-lever seismograph. Ball fell 35 feet, unless differently specified.

Number of fall.	Station.	Maximum amplitudes.		Number of visible vibrations.		Remarks.
		Normal vibrations.	Transverse vibrations.	Normal.	Transverse.	
	feet.	millims.	millims.	millims.	millims.	
17	100	3	2	6	13	Normal vibrations drawn in 1 second, transverse in 2 seconds.
18	100	3	1·5	7	12	Transverse drawn in about 3 seconds (?). In both the above records of the transverse vibrations small irregular ripples apparently due to the direct wave or to a looseness in the joints of the instruments are shown.
21	200	1	1	4	12	
22	200	1	1·5	6	12	
23	200	1	1	6	10	
26	100	2	1·25	16	18	Produced in 4 seconds.
27	100	2	1·25	15	18	„ $3\frac{1}{2}$ seconds. Ball fell 25 feet.
28	100	1	1·5	8	9	„ $3\frac{1}{2}$ „ „ 18 „
30	100	0·75	1	11	16	„ $2\frac{1}{2}$ „ „ 8 „

RECORDS obtained from the rolling sphere seismograph. Ball fell 35 feet.

Number of fall.	Station.	Maximum amplitudes.		Remarks.
		Normal vibrations.	Transverse vibrations.	
	feet.	millims.	millims.	
19	100	4	1·25	18 distinct waves in 3 seconds.
24	250	1	(?)	25* waves. Direction of motion of plate was parallel to the direction of the transverse waves, which therefore cannot be measured.
25	250	2	(?)	34* waves in 10 seconds. The transverse motions are too much compounded with the direct vibrations to be measured.

SIXTH SET OF EXPERIMENTS.

On the line A D.

The only difference between these experiments and the preceding ones is that the smoked glass plate was drawn along parallel to one of the pointers in order to avoid the possibility of any rotational movement taking place. This precaution, although apparently necessary when making experiments for the determination of velocity, does not, in the result, show that the former method gave any errors.

* It is probable that either from bad adjustment of the instrument or from an independent motion of the ground the instrument has exaggerated the duration of the motion in these two cases.

Transverse vibrations.

Fall 32. 250 feet station.

The transverse motion commenced slowly. After 1·5 second it rose to an amplitude of 3 millims., and it continued, but gradually falling, for more than 6 seconds.

Normal vibrations.

Fall 33. 250 feet station.

There appears to have been about 6·5 normal vibrations per second.

The first distinct motion is apparently one of suction or drawing in of the ground towards the point where the blow was struck. The maximum motion is very near to the commencement of the record, which can only be seen for a length equivalent to a period of 3 seconds.

Normal vibrations.

Fall 34. 250 feet station.

About 11 normal vibrations are visible. There appears to have been 5·5 vibrations per second. The amplitude at the commencement is 1 millim. At the end of 1 second it is ·5 millim. This amplitude decreases regularly to zero, which is reached at the end of 4 seconds.

At first there is a *very slight* motion of compression. The first distinct motion is one of suction or drawing inwards towards the weight. The motion reaches a maximum ·25 second from the commencement.

Transverse vibrations.

Fall 35. 250 feet station.

Here there are 6 waves per second. The movement commenced faintly, rose to a maximum of 1 millim. after about 1 second, and then died out as it commenced.

Motion was observed for 4 seconds.

Normal vibrations.

Fall 36. 100 feet station.

The first distinct motion is a rarefaction or drawing in towards the weight. The greatest amplitude is 2·25 millims. Simultaneously with this record, a complete record of the *vertical* motion was drawn. (See seventh set of experiments.)

Seventh Set of Experiments.

These experiments were made for the purpose of determining vertical motion. The instrument employed was a cylindrical tin can half-filled with water, with a flexible sheet indiarubber bottom. As this can is raised or lowered, the flexible bottom

synchronously palpitates. These palpitations are recorded by means of a pointer or lever axled in the centre of the flexible bottom and again to a point in contact with the framework of the can; with this contrivance the actual up and down motion of the bottom of the can is multiplied 21 times.

VERTICAL motion on the line A D.

Fall of ball.	Station.	Rise of ground.	Fall of ground.	Total motion.
32	50	6	3	9
33	100	2·5	2	4·5
35	150	..	..	1
34	200	..	..	0

From this table it will be observed that the vertical motion, which may be a component of the transverse vibrations, dies out very rapidly. The rapid dying out of the vertical movement is possibly due to the free surface. It is remarkable that this wave of distortion should die out so much more quickly than that at right angles to it.

Fall 36. 100 feet station.

Here the vertical motion was registered on a moving glass plate attached at right angles to a plate on which normal vibrations were being written. The first distinct movement appears as if the earth had gone downwards. The double amplitude of the first large wave is 6·5 millims., the downward half of the movement being larger than the upward half. The largest motion to one side 3·5 millims. It diminishes very rapidly at first but afterwards more slowly.

In the following four experiments also made on the line A D, two similar and similarly placed horizontal lever seismographs were allowed to write the movements of the ground simultaneously at two stations. For the object of these experiments, see eighth set of experiments.

Normal vibrations.

Fall 37. 50 feet station.

There were about 8 vibrations per second. The first movement appeared to be one of compression. The vibrations were sensible for 1·5 seconds. The first 2 vibrations are very distinct.

250 feet station.

There were about 8 vibrations per second. The first movement is one of compression. The greatest double amplitude is 1·5 millims. The vibrations are more regular than they are at the 50 feet station. The first 4 vibrations can be easily compared with the first 4 at the 50 feet station.

Normal vibrations.

Fall 38.

These records at the 50 feet and 250 feet stations were very similar to those of the previous experiments.

Transverse vibrations.

Fall 39. 50 feet station.

There were at the commencement 16 vibrations per second. After 1 second there were 8 vibrations per second. This change in the rate of vibration may possibly be due to a disturbance caused by the direct wave, and therefore only apparent.

Vibrations continued for 2 seconds.

250 feet station.

There were about 8 vibrations per second. The greatest double amplitude is ·8 millim. There is no appearance of the rapid vibrations which were observed at the 50 feet station.

The characteristic waves of the 50 feet station can be here recognised.

Transverse wave.

Fall 40.

The character of the vibrations is similar to that of the previous experiment.

Eighth Set (Velocity).

The method first adopted for the measurement of the velocity of transit was to arrange a very sensitive circuit-closer in a position only a few feet distant from the point where the weight fell. This circuit-closer being connected with a pair of wires leading to a chronograph, situated at a point 560 feet distant from the circuit-closer, served to bring this chronograph in action. An observer stationed beside the chronograph, with his hand on a contact key, broke the circuit at the instant the surface of mercury in a vessel placed on the ground beside him was set into vibration. The corrections, personal and instrumental, in this method were evidently somewhat difficult, and it was abandoned before any very good results were obtained by it. The lowest result obtained by this method was about 380 feet per second and the highest about 930 feet, the average being 630 feet. The explanation of this very high result was no doubt to be found partly in the circuit-closer, which was at that time in various ways imperfect, and partly in the fact that the fall of the weight could be readily heard through the air. This may have caused the observer to anticipate the very small vibration which was produced in the mercury. The circuit-closer was caused sometimes by the rapid up and down movement of the earth to leap out of contact immediately after having closed the circuit; in such cases the chronograph did

not act until the circuit became permanently closed. The result of this was evidently to reduce the apparent time of transit and hence increase the velocity.

The second cause of error above indicated was rendered very likely by the fact that the motion of the machinery in the works kept up a continual vibration in the ground.

An automatic circuit-breaker was next introduced into this arrangement and the distance reduced to 200 feet. A correction for instrumental error was in this case determined from observations at 100 feet. With this arrangement a mean velocity of transit equal to 563 feet per second was obtained.

The state of the ground was in this case affected to some extent by frost, the temperature the previous night being 9° Fahr. below freezing.

The circuit-closer was next altered and three more determinations made, the mean result of which gave 379 feet per second. In this case, however, the previously determined correction had to be used owing to the fact that a new correction could not be made that day, and was not afterwards made.

This result is somewhat uncertain, because a new circuit-breaker was here used and more improvements introduced in the closer.

Neither of these methods having given results with which we felt at all satisfied, we turned our attention to the registration of the motion of the ground in conjunction with the time. We were led to this method of experiment through some trials of a seismograph, designed by one of us, which we had taken advantage of these experiments to make. This instrument (GRAY's rolling sphere seismograph) proved so sensitive that the motion of the ground could be plainly written at a distance of about 400 feet. The first trial of this method was made as follows:—A glass plate mounted on three wheels was arranged in such a way that it could be pulled forward uniformly by clockwork under the writing point of the seismograph. A separate arrangement consisting of an electromagnet and writing levers was fitted to write on the same plate. This electromagnet was placed in circuit with the circuit-closer previously used, and hence when the circuit was closed a mark was made on the plate; a short time after this the seismograph began to write, and the interval between gave the time of transit subject to the error of the circuit-closer. The error of the circuit-closer was again determined by bringing the recording apparatus 150 nearer to it. This, however, also proved inconvenient and on the whole unsatisfactory, as it caused a great number of somewhat laborious experiments to be made which could be obviously avoided by doubling our apparatus and taking the difference of time between two stations. The propriety of using an instrument which would only record a component of the earth's motion soon suggested itself when we came to consider the question of the relative velocities of the direct and transverse vibrations. A very approximate estimate of this could be got by the instrument just mentioned, but as it wrote the resultant motion there was a little difficulty in determining the exact point at which the transverse wave became felt. To get over the difficulty we had recourse to a pair of horizontal lever seismographs in our possession. These instruments have already

been referred to, and for a full account of them see Transactions of the Seismological Society of Japan, vol. ii.

The measurements made by the first method here mentioned gave a velocity of transit equal to 446 feet per second for direct and 353 for transverse wave.

The individual experiments in this case give for direct wave 454, 446, 436, 449, for transverse 360, 345.

By the second method, which evidently requires no correction of any kind except for clock rate, we obtained a mean velocity of 396·5 feet for direct wave.

The individual experiments being 399, 394, the mean velocity for transverse wave was at the same time found to be 360 from two experiments giving respectively 367 and 353, the rate at which the plate moved was determined by causing a small pendulum to act as a periodic circuit-closer, and by so doing to make a series of marks simultaneously on the two plates at distances apart which represented in the actual experiments $\frac{10}{20}$ths of a second of time.

The variations in velocity, although partly due to different methods of experimenting, were no doubt to a certain extent due to different conditions of the soil, there being a variable amount of frost during the period (somewhat extended) which we found necessary for the whole series of experiments.

The difference between the results of the last two methods are probably due to difference in the ground. An interval of more than a week intervened between these two set of determinations, and in the meantime the weather had changed from a minimum temperature a few degrees below zero to a minimum temperature a little above zero.

Giving double value to the last two sets of experiments and leaving out altogether the first set we obtain a mean velocity for the direct wave of 438 feet. Again, from the last two sets we get a mean of 357 for velocity of transverse wave. These results are probably near the truth.

Description of Figures.

PLATE 52.

Fig. 4. (See fifth set of experiments, fall 25). This shows a representation, magnified two and a-half times, of the diagram drawn at the 250 feet station by the rolling seismograph.

The arrow crossing the diagram shows the direction of the direct wave. The first two vibrations are apparently normal ones, but the succeeding waves show the interference of these vibrations with transverse motions.

The most interesting point about the diagram is, perhaps, the evidence of a cycle which is passed through in about five vibrations. Corresponding vibrations are similarly numbered.

Fig. 5. (See fifth set of experiments, fall 17.) Fig. 5 is a representation, magnified two and a-half times, of the record taken by two horizontal lever seismographs at the 100 feet station for the 17th fall of the ball.

The line A represents the record of transverse vibrations, and B that of the direct. These two sets of vibrations were recorded simultaneously on the same plate. The direct vibrations are apparently more rapid than the transverse ones.

The chief point to be observed about this diagram is that the normal vibrations commence a short time before the transverse ones.

It will be observed that although the normal vibrations are at first greater in amplitude than the transversal ones, they die out more quickly than the latter.

Corresponding points in time are joined by cross lines.

This record may be taken as characteristic of other records taken in the same manner.

Fig. 6. (See seventh set of experiments, fall 36.) This diagram shows a magnified record of the normal vibrations on the line A, and vertical vibrations on the line B, as taken simultaneously at the 100 feet station. It will be observed that the vertical motion like the transverse motion is a little behind the direct motion. This we should anticipate, the vertical being like the transverse, a wave of distortion.

Fig. 7. (See sixth set of experiments, fall 33.) This diagram illustrates one of the methods adapted for the determination of the velocity of propagation. In this method a circuit-closer and seismograph were used (see eighth set of experiments).

The diagram was drawn at the 250 feet station, and as shown on this paper has been magnified two and a-half times.

The upper line was drawn by a point on the end of the lever which could be deflected by an electromagnet, which magnet was in electric connexion with the circuit-closer placed near the falling ball.

The lower line shows the diagram drawn by a horizontal lever seismograph, arranged to record normal vibrations. The portions a b were drawn before the circuit was closed by the fall of the ball; when the circuit was closed near to the ball the pointer of the electromagnet was deflected to c and held deflected.

The plate travelled the interval represented by b' d' before vibrations commenced to be recorded at the 250 feet station.

Fig 8. (See seventh set of experiments, fall 37 or 38). This diagram is a magnified representation of two records of normal vibrations taken simultaneously, the upper one at a 50 feet station and the lower one at a 250 feet station on the same line. Corresponding points *in time* on these two diagrams are marked with similar figures.

The chief point illustrated is the last and probably the best method of obtaining velocity.

By comparing the two records we see that vibrations took place at the 50 feet station considerably before reaching the 250 feet station.

By measuring the interval between similar points, as for instance the beginning of the motion on the two diagrams, the time taken for the vibration to pass from one station to the other can be calculated, and from this the velocity of propagation between these two stations deduced. This method of experiment has the great advantage that no instrumental error can enter into the result. It is of course possible that a vibration which reached the 50 foot station, and was there registered as the beginning of the motion, might not reach the 250 foot station with sufficient amplitude to be registered. An error from this cause can, however, be easily avoided by an examination of the records.

General Conclusions.

The first set of experiments, which was an attempt to obtain an estimate of the rate at which a disturbance produced at a point on the earth's surface is absorbed, were not very satisfactory. The times which the mercury continued to vibrate at the various stations, as given by various observers, did not agree well with each other, and no doubt depended to a great extent on the mode of observing. When, for instance, the reflection of the sun from the surface of the mercury could be seen, the motion could be detected much longer than when a diffused light was used.

The observations all show a dying out of the vibration, as a matter of course, but the only interesting observation is the total cutting off of the vibration by the pond when the point of observation was at a sufficient distance from the corner. This shows that the motion observed near the corner must have been due to the creeping round of the vibrations transmitted along the side. More definite information is given by the second set of experiments. These show that the vibrations which pass up the hill and round the pond are for the most part transverse.

In the third set of experiments we have evidence from the written records that the amplitude of motion is nearly inversely as the distance. The change in the nature of the ground under the falling weight interfered considerably, however, in these experiments. The character of these static records is also very interesting, as this no doubt

gives a good indication of the nature of the actual movement in the earth. It would appear also from these, and from subsequent records, that the direct vibrations, although the largest at first, die out more rapidly than the transverse motions. This may have an interesting bearing on the direction observations in earthquakes.

The apparently quicker rate of vibrations of the normal motions, as compared with the transversal movements, is a point worthy of attention. Also the quicker rate of either of these sets of vibrations as compared with the average rate of vibration as experienced in any of the recent earthquakes in Tokio may be noticed. It may also be remarked that the actual earthquake records show a motion which is usually exceedingly irregular.

The actual displacement of a particle from its normal position in the artificial disturbances seems never to have been above 0·5 millim. at a distance of 50 feet, and at a distance of 250 feet it seems to have been from 0·1 to 0·05 millim. Perhaps the most remarkable point made out from these experiments is the very slow rate at which the disturbance is propagated. The experimental verification of the slower rate of propagation in transverse vibrations is also interesting.

This slow rate of propagation accounts for the observation, so often made when earthquakes take place in Tokio, that a rumbling sound precedes them. This rumbling sound is no doubt in many cases the cracking and creaking of buildings reaching the ear through the air sooner than the disturbance in the ground becomes sensible. It is possible that very reliable observations of direction and locality from which the disturbance emanates may be founded on this.

In conclusion, we beg to tender our best thanks to the directors of the Akabane Works for the facilities given for the carrying out of our experiments; to the Telegraph Department for the loan of wire; to Messrs. TAMAKI, KITAKA, and other gentlemen who from time to time afforded us assistance in taking observations.

Fig. 4.

Fall 25. (See Fifth set of Experiments.)

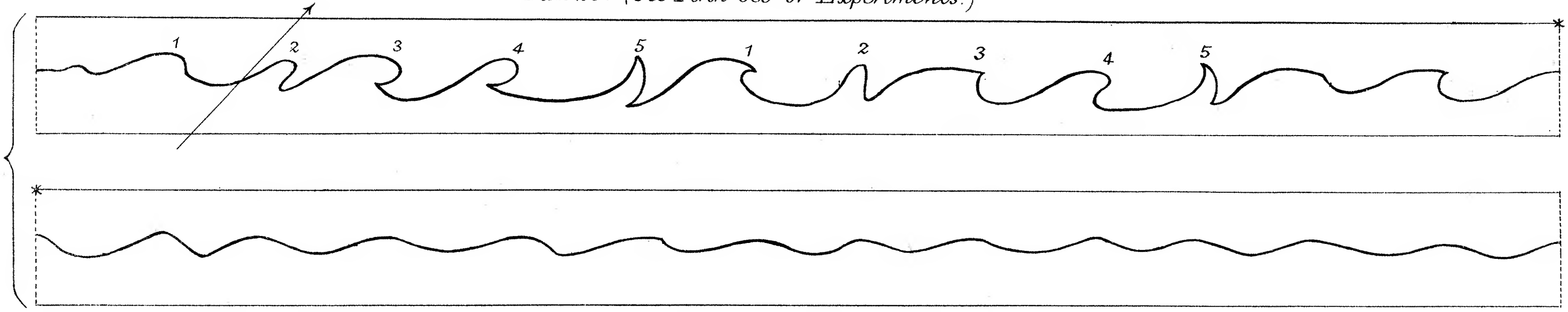


Fig. 5.

See Fifth set of Experiments. Fall 17.

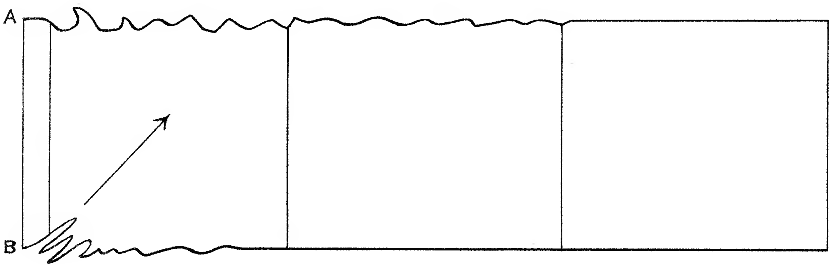
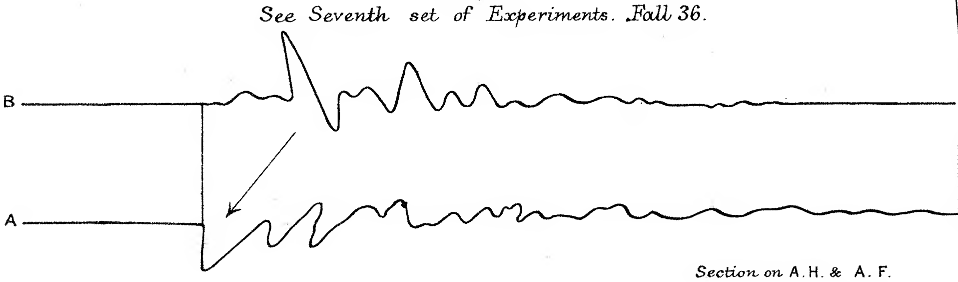
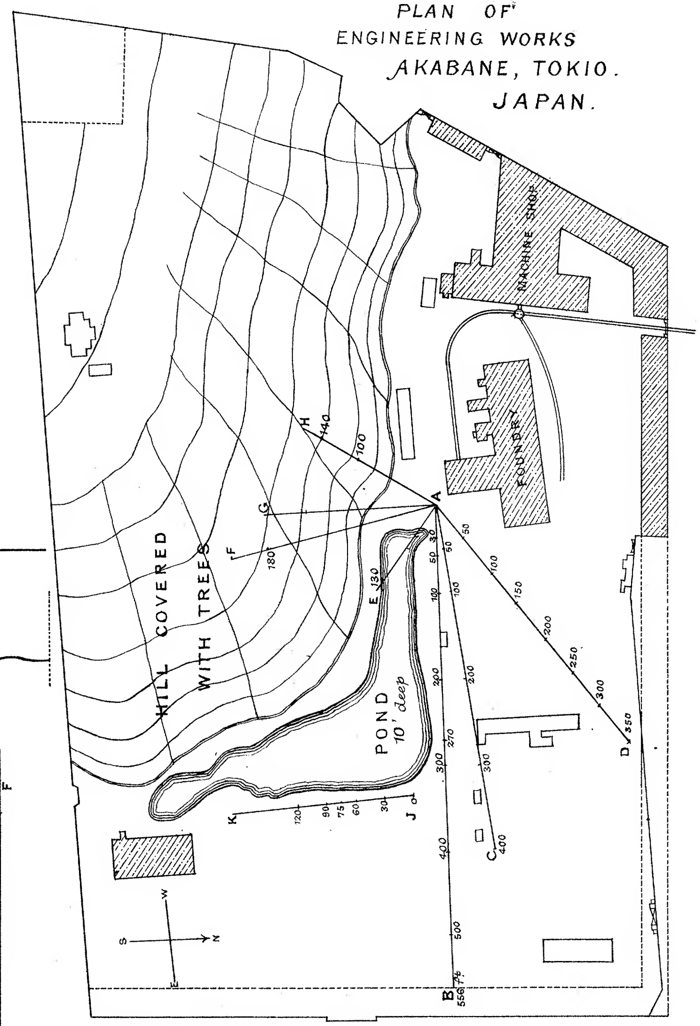


Fig. 6.

See Seventh set of Experiments. Fall 36.



PLAN OF ENGINEERING WORKS AKABANE, TOKIO. JAPAN.



SCALE: $\frac{3}{32}$ inches = 20 feet for Plan.
" = 40 " for vertical Scale in Sections.

Section on A.H. & A.F. on Plan.

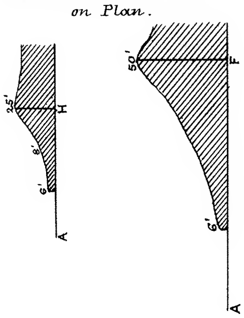


Fig. 7.

See Sixth set of Experiments. Fall 33.

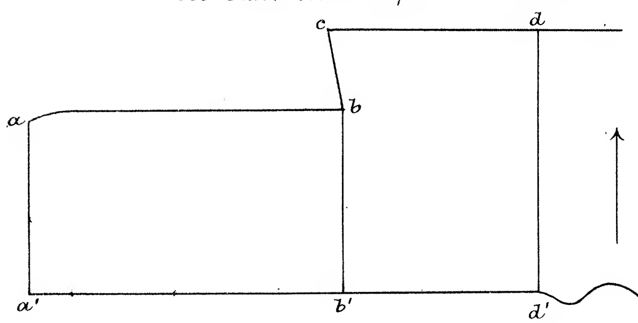
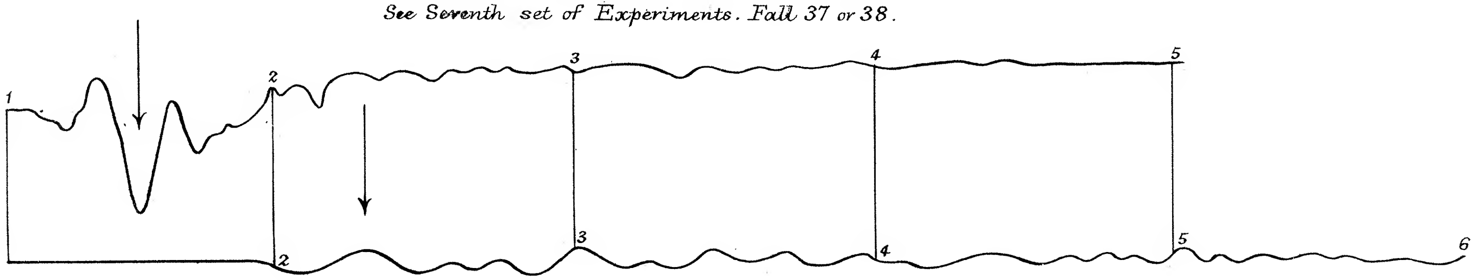


Fig. 8.

See Seventh set of Experiments. Fall 37 or 38.



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